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Tolerance Simulation in the Assembling Process based on Experimental Data from Series Production

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Abstract

The automotive industry is affected by rising quality requirements for modern cars more than ever. Shortening the development period may involve cancelling the hardware prototype phase, without which the learning process of parts and assembling behavior in the assembling process is omitted. In this context, the subject of dimensional management and especially tolerance simulation is an essential tool. For the digital prototyping phase it is essential that the simulation rebuilds the real processes. Through the process of validation by production tests, the simulation model becomes more precise, which is necessary to be faster in the subsequent digital concept validation processes. This paper establishes the challenges in simulating real assembly processes in conventional tolerance simulations. It emphasizes the limits of simulating real processes and component behavior in conventional tolerance simulations. The real process with all possible shim settings cannot be simulated using the simulation tools due to the limited datum targets which can be set. Furthermore the component behavior itself should be integrated in the simulation model to get results that are closer to reality, because the reinforcement parts and the alignment scheme are important for assembly accuracy.

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Keywords: development process; assembling accuracy; tolerance simulation; experimental data; verification

1. High Quality Requirements in the Automotive Industry

The automotive industry is affected by rising quality requirements for modern cars more than ever. There is stiff competition to produce the highest quality of cars. The later the production faults are discovered and fixed, the more costs are involved for the manufacturer. Early quality control in the single part stage regarding accuracy and usability for the assembling stage will lead to a reduction of rework and scrap. However the high level of control is not always viable or may just be too expensive in terms of either the investment costs involved or the associated increase in cycle time. Therefore, it is vital to secure the component concepts during the development process, to prepare worst-case scenarios and to compile statistic tolerance calculations or simulations. However, shortening development periods contrast with extensive concept validations.

1.1 Modern Dimensional Management for Modern Development Process

Shortening the development period may involve cancelling the hardware prototype phase, without which the learning process of parts and assembling behavior in the assembling process is omitted. This implies that the production team cannot gain relevant experiences in that state. Before such reorganization the concept validation process was an iterative one, also making use of the hardware phase. These requirements call for new methods of concept validation. In this context, the subject of dimensional management and especially tolerance simulation is an essential tool. So far the input parameters of tolerance calculations and simulations

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have been based on experienced data of parent and similar model series, which are able to depict reality in a rather simplified manner. The data thereby also produces concept validation at a very simplified level. For the initial iterative component validation process carried out during the different steps, such input data was enough. Now however, higher requirements for the tolerance simulation exist.

The body-in-white, as an example, requires several hundred components to be processed. These different components require varying numbers of production steps before reaching the assembly stage. All these assembling stages have been built in a digital way to secure the concepts.

In a modern development process top priority is given to saving time. The developers have to be efficient and avoid any additional tasks. Consequently, the common practice is to adapt prior tolerance simulation to estimate the current components or assembly behavior. Depending on the different component geometries and the different production steps, the tolerance input data for all subsequent projects is often generalized. Figure 1 shows the information flow of the actual concept validation process by using simulations.

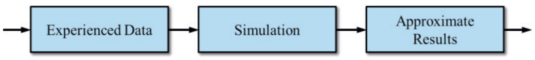

Fig.1. Flow chart of tolerance simulation wherein results are based purely on experienced data of parent and similar model series.

To improve quality of existing tolerance simulations it is necessary to identify the most influential components for the assembly, the real behavior of the components and the process itself. The simulations conducted must produce results that are closer to reality. For this purpose measurement data and simulation data have to be compared which requires measurements to be made in the stamped part state as well as in the assemblies built by the measured stamped parts. This is important to get more know-how of simulations behavior to use the tools more precise.

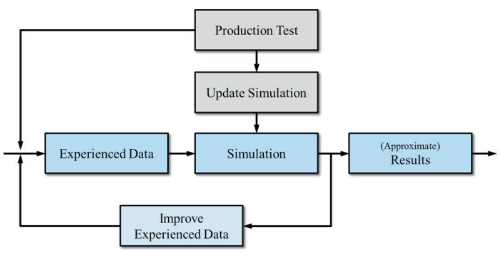

Fig.2. Flow chart of updated tolerance simulation wherein experienced data are improved by production tests.

Through the process of validation, the simulation model becomes more precise, which is necessary to be faster in the subsequent concept validation processes. As a result another output is generated, which can be used as input for improvement in experienced data (fig 2). Production tests during series production are essential to update human know how. The validation just passes off in digital experiments. For the digital prototyping phase it is essential that the simulation rebuilds the real processes. In order to validate the real process fluctuation and real stamped part behavior in the production test it is important that it is located after job no. 1 Other enforcements would bring inaccuracies again.

2. Theoretical Background

2.1. Required Sample Size

A production test in series production is accurately planned. Every intervention in a body-in-white production entails costs for the manufactures. The highest priority for a production test is to make it economical and maximize the benefit.

In order to get a statistically relevant result from the production test, preliminary considerations have to be determined. At first the specific aims of the production tests should be defined. Secondly the experimental variables need to be considered. The most important statistical values are the mean value and the specific values of the distribution, for example the standard deviation of normal distribution [1]. Normal distribution is the commonly used distribution of process fluctuations [2].

According to [3] measurement of three to five different parts is enough to get the mean value of the total population. As opposed to that, for the standard deviation a larger sample is required. Generally the standard deviation of a sample is not equal to the standard deviation of the total population. The correlation is described by the confidence interval [4] (1).

$$I(x_1 \dots x_n) = \left[\sqrt{\frac{(n-1)\cdot s_n^2}{\chi^2_{n,1-\frac{\alpha}{2}}}}, \sqrt{\frac{(n-1)\cdot s_n^2}{\chi^2_{n,\frac{\alpha}{2}}}} \right] \quad (1)$$

I	Confidence Interval
n	Sample Size
α	Probability
χ	Quantile of the chi-square distribution
s	Standard Deviation

The bigger the sample size, the smaller the confidence interval [5]. Figure 3 shows how big the error of the standard deviation in relation to the used sample size can be. In comparison to the method used to get the mean value it is obvious that a sample size of 5 is too less because it implies a big error.

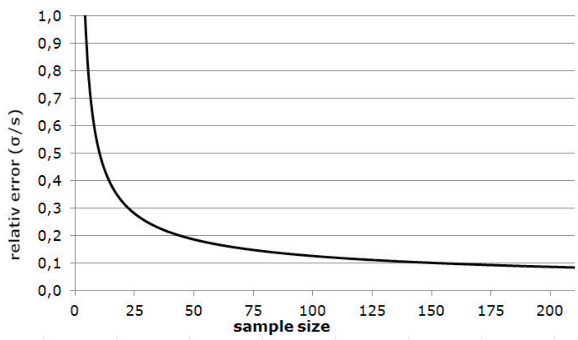

Fig.3. Error between real and measured standard deviation in relation to the sample size

As noted in figure 3, the sample size must be greater than approximately 50 as this size has the best effort-benefit ratio, which is shown in practice. Further, to maximize benefit, the sample size should be split into subsamples with smaller parts

[3]. In this process a wide variety of information can be covered. Therefore, for our project a sample size of 60, split in two subsamples, has been used.

2.2. Measurement Method

Modern measurement systems are comprehensively applied in the modern automotive industry. The measurement methods are used to find out the accuracy of a part or an assembly. The accuracy δ is defined as the difference between the nominal value and the actual value. To integrate the measurement values in conventional tolerance simulation some aspects need to be considered. It is important that the direction of measurement is the same as the tolerance specification. Tolerance specifications of surfaces and trimmings are always specified in normal to a surface direction. Directions of measurement, which are not in this direction, for example parallel to the coordinate system or in other directions because of the possibility to catch the right points, would need to be converted to that direction. In the automotive industry the most used tolerance simulation tools are 3DCS and Teamcenter VisVSA. Both simulation tools are possibly used with measurement data as input data.

For the following analysis, coordinate measuring equipment with a tactile sensor for measurement of stamped parts, and an optically measured system for the assemblies is used. The measurement results of the optical sensor have been calibrated with measurement results of the tactile sensor. Apart from the measuring equipment, the component/part reference system and the exact adjustment are also important to get usable values [6]. The same part is measured five times to test the ability of measurement equipment. For each measurement the part is removed from the alignment scheme and put in again [7].

3. Concept and Thematic Focus

In this paper the method to analyze a series production test, with an example of a component from body-in-white process, will be presented. The approach is shown in figure 4.

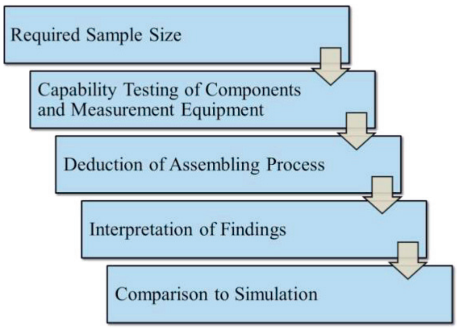

Fig.4. Method of Analysis

In our research project a trunk lid was used for investigation. A trunk lid is an interesting assembly because it is characerized by a frame hemming the outer edges. Every sedan has one, and it is important as it has many gaps and flushs, which can be evaluated by costumers. According to that, the trunk lid has high qualitiy targets.

Chapter 2.1 describes how the sample size is determined. For the present analysis 60 parts of each stamped component, splitt in two subsamples with 30 parts each, are measured. The trunk lid consists of seven stamped parts. Two of them are flexible stamped parts, one is a connecting plate between the flexible stamped parts and four parts are rigid stamped parts to reinforce the assembly (figure 5).

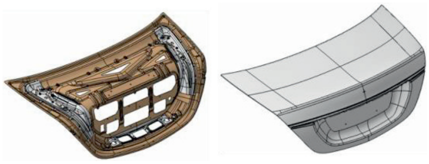

Fig.5. Example of assembly: trunk lid; left: reinforcing assembly; right: covering assembly

To test the accuracy of the measurement values, a capability testing is conducted. For rigid stamped parts it is easier to fix the part on the measurement machine, unlike the flexible stamped parts. The capability testing for the present analysis confirms this assumption. The analysis exposes up to 0.6 mm difference at the points of measurement on the flexible stamped parts. This points out the high influence of the machine operator and the alignment scheme on the measurement results. With reference to that, the measurement results of the flexible stamped parts have to be handled with care. New methods for measuring flexible stamped parts without deforming, and independent from the machine operator, have to be developed for subsequent analysis.

To reconstruct the component's influence on the assembly accuracy, continuous measurement chains have to be constructed. The stamped parts have to be measured at the same point in the single part state as in the assembly stage. This paper will focus on the assembling process, which fixes the covering assembly, including the flexible stamped parts and the connecting part, to the reinforcing assembly. To fix these assemblies the process of hemming is conducted. Some other publications already discuss the hemming process and their simulation. The following analysis does not challenge these because most of them are engaged in the springback process and FEM simulation [8], [9]. This paper will focus on the comparison between real component behavior based on real measurements and tolerance simulation. For results concerning FEM Simulation see [10] or [11]. In [11] a new method for FEM simulation of assembling process is designed, which focuses on the forming and welding process to estimate the component's behavior one of which is also the springback effect, noted in earlier publications.

However there are no publications concerning tolerance simulation, hemming process and measurements from series production. Therefore a new research opportunity exists. Research can be conducted on the specific question concerning the assembly behavior of stamped parts and the assembling process, as well as the way of proving and simulating the above, using conventional tolerance simulation tools. Basically Bohn and Klinger [12], [13] are engaged in analyzing the deviation of stamped parts concerning stiffness and geometry as well as rerouting real-life data in the development processes for updating experiences.

4. Analysis of the assembling process by using measurement data

4.1 Preliminaries

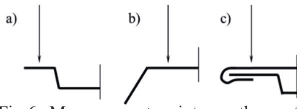

Fig.6. Measurement points on the parts and the assembly; a) flange of the inner reinforcement part, b) flush of the outer covering panel, c) flush of the assembly

For improve the tolerance simulation the production test should show the important points which have to be included in the subsequent tolerance simulations. The following sections put forth the meaningful results of the analysis. The focus in this analysis is on the flush to other parts which is characterized by the flush of the assembly (fig. 6c). This in turn is characterized by the flange of the inner reinforcement part (fig. 6a) and the flush of the outer covering panel (fig. 6b) which is measured. Measurement chains have been built to analyze the behavior of the assembly vis-à-vis the stamped parts. For this example, four measurement points are chosen across each area depicted in figure 7.

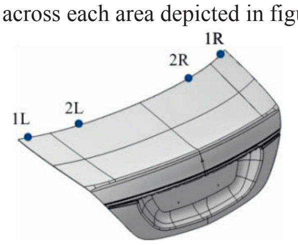

Fig.7. Location of analyzed measurement points (1L, 2L, 2R, 1R)

4.2 Deduction of the Assembly Process

4.2.1 Flexible stamped Parts

The measurement values of the covering panel have to be considered with caution according to chapter 3. Table 1 shows the mean values and displacements between the subsamples as well as table 2 shows the deviations. It does not show differences between the mean values of the different subsamples, only for the measurement values at measurement point 1R. As explained before measured values of flexible stamped parts are influenced by alignment scheme and the machine operator. This displacement could be a mean value displacement, but it is also possible that only the process of adjustment and the gravity induce these inaccuracies.

Table 1. mean value of covering panel

Covering Panel /in mm	1L	2L	2R	1R
Mean Value Subsample 1	0.926	-0.019	-0.043	0.994
Mean Value Subsample 2	0.899	-0.017	-0.062	0.860
Mean Value Displacement	-0.027	0.002	-0.019	-0.134

Furthermore there is as well no standard deviation displacement between the subsamples, only at measurement point 2R. In this subsample an irregularity can be observed (see description below in this paper). Without this value, there is only a very small displacement between the subsample deviations.

One can thereby state that without the development new methods to measure flexible stamped parts excluding the influence of the alignment scheme or the worker, valid conclusions cannot be reached.

Table 2. standard deviation of covering panel

Covering Panel /in mm	1L	2L	2R	1R
Deviation Subsample 1	0.031	0.026	0.049	0.048
Deviation Subsample 2	0.039	0.027	0.181	0.056
Deviation Displacement	0.007	0.001	0.133	0.009

4.2.2 Rigid stamped Parts

Regarding the inner reinforcement, a mean value displacement can be observed between the two subsamples which may be a result of tool changing in the press shop (table 3). This significant difference makes the measurement values interesting to analyze. As well as the deviation of the flexible parts the deviation displacement between the subsamples of the inner reinforcement is marginal.

However the mean value displacement lies between 0.2 and 0.6 mm. This is a big change concerning tolerance specification which are normally only up to +/- 0.5 for mold surfaces on single parts in the automotive industry.

Table 3. mean value of inner reinforcement

Inner Reinforcement /in mm	1L	2L	2R	1R
Mean Value Subsample 1	-0.182	0.007	-0.001	-0.480
Mean Value Subsample 2	-0.578	-0.603	-0.599	-0.273
Mean Value Displacement	-0.395	-0.610	-0.598	0.206

But there are not only mean value displacements between the subsamples but also between the measurement points within one subsample. The values of 1R have a mean value displacement with the other points in each subsample. This fact points to the torsion inside the flange of the inner part. In the first subsample it is torsion to the negative, in the second subsample it is torsion to the positive.

4.2.3 Assembling stage

Furthermore, after looking at the stamped part measurement data, the assembling stage measurement data will be analyzed with respect to the aforementioned facts on stamped parts.

Deviation

The trend of the deviation is not transferred through the assembly process from the stamped part to the assembly. In a modern body-in-white process there are many different joining processes and external influences which cannot be eliminated. The accuracy is affected by all these influences thereby leading to only a marginal correlation of values between the graph’s deviation of the stamped parts and the assembly. Nevertheless the deviations of the assemblies between the subsamples also are small (table 4).

According to (1) there could be a mistake less than 20 % of the deviation. That means the mistake is arranged in a range of a few hundredth which is acceptable related to the measuring fault.

Table 4. standard deviation of assembly

Assembly /in mm	1L	2L	2R	1R
Deviation Subsample 1	0.150	0.091	0.073	0.132
Deviation Subsample 2	0.190	0.082	0.090	0.177
Deviation Displacement	0.040	-0.009	0.017	0.045

Mean value

The mean value displacement at 2L as well as the mean value displacement at 2R of the reinforcement subsamples is transferred to the assembly subsamples. Table 5 describes the process of transfer. At measurement point 2L the mean value displacement is seen as nearly 1:1, in contrast to measurement point 2R. The same needs to be examined more closely (see description below in this paper).

Table 5. mean value displacement

	2L	2R
Mean value displacement inner part	-0.610 mm	-0.598 mm
Mean value displacement assembly	-0.557 mm	-0.864 mm
Difference between the mean value displacements	+9%	-44 %

Table 6. mean value displacement Assembly

Assembly /in mm	1L	2L	2R	1R
Mean Value Subsample 1	-0.508	0.282	0.654	0.420
Mean Value Subsample 2	-0.161	-0.275	-0.210	0.246
Mean Value Displacement	0.347	-0.557	-0.864	-0.174

At point 1L there is a mean value displacement in the stamped part and in the assembly, as seen before. The significant difference is that the mean value displacement of the assembly is the other way around. Between the two production tests, the position of the area of measurement point 1L was adjusted about +0.5 mm in z-direction by shims. That explains the mean value displacement of the assembly at point 1L. The influence of the inner part is affected by shims (table 7). Nevertheless the springback effect described in publications as outlined above is apparent, that is proved by the mean value displacement smaller than 0.5 mm which was adjusted by the shims.

At point 1R the same situation of the mean value displacement is displayed in the other way around. The torsion of the flange of the inner part can also be seen in the assembling values. A negative torsion acts as a positive torsion in the assembly and other way around. The same can also influence the measurement values of 2R. That is the reason why the mean value displacement at that point is bigger than that on the mirror point on the other side (table 5).

Table 7. mean value displacement

	1L
Mean value displacement inner part	-0.395 mm
Mean value displacement assembly	+0.347 mm
Shims	+0.5 mm

As outlined above in the values of point 2R of the covering panel an irregularity exists, which is larger than 0.8 mm. This might be due to a defect in the covering panel. The defect is also apparent in the assembly line but is much smaller. However the size of the irregularity is less than half. This might be because of the methods of measurement adopted. Through a marginal shift in the measurement equipment, another point is measured, at which the defect is not too significant (figure 8). Irrespective of that, the covering outer part has least influence on the assembly accuracy. Only the defects are noticeable, while other correlations cannot be distinctly seen.

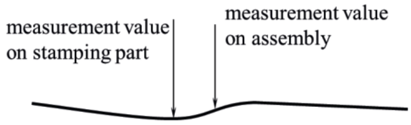

Fig.8. Explanation of different measurement values at the “same” point

All in all the accuracy of assembly is affected by many influences. The main influences are the assembling process and the reinforcements. The covering parts and other external influences have only minimal influence.

5. Comparison of the measurement data and a tolerance simulation model

Simulation results are only as good as the model is. Building a model requires much intuition and experience. The experience is gained through production tests. This concerns not only tolerance simulations but rather all simulation methods. The results are highly dependent on the boundary conditions or rather the input data. To simulate the highly complex body-in-white production some assumptions have been taken. The hemming die of a trunk lid has more than 40 fixtures and clamping components. Conventionally tolerance simulation tools use the three-two-one principle to fix a part in the simulation space.

Excurse: Three-Two-One Principle

Wherein the primary datum plane is built by three points, the secondary datum plane is built by two points and the normal vector of the primary plane, and the third plan is formed with the normal vectors of the primary and secondary planes and a point (fig. 9) [1]. This rule completely describes a part in the simulation space.

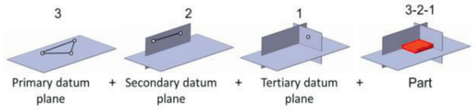

Fig.9. Three-two-one principle [1]

However this principal conflicts with complex assembling processes in tolerance simulations. The principle is only usable for real rigid parts or really approximated results – not for flexible parts and deformation effects of assembling processes.

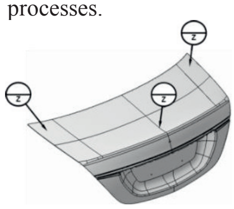

Fig.10. Example point of primary datum plane

The next conflict is that if the shim process is reproduced in a tolerance simulation, more than 40 fixtures would have to be reduced to six points. At this moment in conventional tolerance simulation, it is not possible to simulate all possible shim settings. For example the simulation is arranged with the most externally laid shims in z-direction (fig 10), which fits with the used shims between the subsamples in the production test.

The virtual shim process does not consider the springback effect after removing the assembly from the hemming die. Furthermore the simulation cannot show the forces dependent on deformations. Table 8 shows these observations.

Table 8. Component adjustment using shims in simulation

	1R
Mean value without shim	0,00355 mm
Mean value with shim (+0.5)	0.535 mm

6. Conclusion

This paper establishes the challenges in simulating real assembly processes in conventional tolerance simulations. It emphasizes the limits of simulating real processes and component behavior in conventional tolerance simulations. The real process cannot be simulated using the simulation tools due to the limited datum targets which can be set. Besides, the component behavior itself should be integrated in the simulation model to get better results. The reinforcement parts are important for assembly accuracy. Therefore the mean value of each batch has to be integrated in the simulation for more precise results. That means the stamped part becomes deformed before reaching the assembly stage. This cannot be easily embedded in conventional tolerance simulations and needs more complex steps like the autobend move. Furthermore a simulation testing should be conducted using real standard deviation and not only generalized or specified values. The standard deviation of the assembling is affected by many influences from the assembly process and others, which are not comprehensible at this moment. Only one thing can be highlighted here, which is that strains in stamped parts or in the assembly tend to affect deviations.

Without other influences, the accuracy of the assembly is affected by reinforcements. The shims method has a big influence on the assembly accuracy as well and overlaps the accuracy of the reinforcements. In this case the springback effect tends to be a lot more significant in the assembly. Due to the above, the alignment scheme has the most important influence in the assembly process. If the alignment scheme is not accurately used, for example if the inner part does not lie at the midpoint of the hemming die, the assembly accuracy can be affected. In the tolerance simulation this information has to be integrated to get better approximated results that are closer to reality. Without use of these facts, tolerance simulation is susceptible to manipulation and may not be usable for procuring more experience about the assembly behavior and the assembling processes, like hemming. Due to development periods becoming shorter and appearance of more digital prototype phases, the tolerance simulation process becomes more important than ever. It is time to develop new methods to reproduce real assembly processes in conventional tolerance simulation not only in FEM. The measurements and the experimental results described in this paper are the first step and serve as the basis for further research.

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